Collapse of a Taylor bubble at free surface: An experimental investigation

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Abstract An Experimental investigation is performed to study the bursting of the Taylor bubble at free surface and film collapse around the bubble. The study is conducted for only circular tube in vertical position with different liquids (water, mustard oil, glycerin, and silicon oil) as bulk. Experimentally collapse of Taylor bubble is tracked at the free surface with different tube diameters (19 mm and 28 mm) by proper arrangement of high speed camera (3000 frames/second) and light. Profile contour of bubble at different stages of bursting process is traced which reveals bubble top film and wall thickness variation with time. Behavior of Taylor bubble collapse in different liquids is explained thoroughly by using visualization and photographic recording technique.
Keywords: Taylor Bubble, Liquid Drainage, Collapse, Thin film

1 Introduction

Motion of a Taylor bubble in a conduit is the simplest possible two phase configurations, which is commonly encountered in many industrial as well as daily life applications. Though bubble bursting at free surface is a very common topic in boiling, cold drinks, bioreactors, glass blowing, ocean study, alcoholic beverages etc., but bursting of Taylor bubble at free surface is not tried in details so far. Unique static shape of Taylor bubble and surrounding liquid film makes the phenomena more complex and challenging. Present study reports the experimental and observations of the collapse of gaseous Taylor bubble in the circular tube. One can clearly identify that after approaching at the free surface, there exist three stages in bubble lifetime. At the beginning the liquid film retracts quickly from center towards the pipe wall. Next, the annular vertical liquid film thins down for a very short span and at the end it collapses to regenerate the free surface. Properties like viscosity of the liquid and surface tension both play an important role in the collapse phenomena. The tendency of wake formation with satellite bubble has been observed to decrease with increasing viscosity of the liquid. Tracking of liquid film drainage during bubble burst at interface reveals that the rise velocity of bubble decreases as liquid viscosity increases. It has been also found out that bursting time of the bubble at interface increases as the viscosity of liquid increases.
Complexity increases when the Taylor bubble approaches the free surface and bursts giving rise of film collapse around the bubble. But due to non-intuitive and counter-intuitive nature of two phase interfacial behavior, physics of movement of Taylor bubble is not yet fully understood. Experimental and numerical efforts are still on to predict the velocity and shape of Taylor bubble. Bhusan et al. [1] have investigated experimentally the rise of Taylor bubbles in narrow rectangular channels for both stationary and moving liquids. They have revealed definite influence of channel orientation, dimension and inclination on the propagation velocity of Taylor bubbles. Ghosh et al. [2] have studied numerically the motion of asymmetric Taylor bubble and Taylor drop in inclined channel by using 3-D lattice Boltzmann method (LBM). They found asymmetry in shape of the rising bubble across the column axis. Gupta et al. [3] have applied computational fluid dynamics (CFD) to model Taylor flow in micro-channels. The liquid film around the Taylor bubble is very thin at low Capillary number and requires careful modeling to capture it. Hua and Lou [4] have developed one numerical algorithm for front tracking method which simulates the rising of a bubble in quiescent viscous liquid due to buoyancy. Qian and Lawal [5] have investigated numerically on the gas and liquid slugs for Taylor flow in T-junction microchannel. Annaland et al. [6] have studied the numerical simulation of gas bubbles behavior using 3D volume of fluid (VOF) method. This model can handle a large density and viscosity ratio and a large value of the surface tension coefficient. Liu et al. [7] have made analysis experimentally on two-phase flow hydrodynamics in vertical capillaries of circular and square cross sections by using air as the gas phase and water, ethanol, or an oil mixture as the liquid phase. Clanet et al. [8] have studied the rising velocity of long bubbles in vertical tubes of different cross-sections, under the action of acceleration due to gravity. Mandal et al. [9] have studied experimentally on the shape and stability

of liquid Taylor bubbles and liquid. Das et al. [10] have investigated the rise velocity of Taylor bubbles through concentric annuli.

2 Experimetal details

Experiments have been performed with different liquids in the vertical tube with proper arrangement of bubble producing quick closing valve and ball valve as shown in Figures 1 and 2. All experiments are carried out by using Perspex material tube. There are three sections in the Experimental set up, namely, (a) liquid drainage and air inlet section, (b) bubble producing section, and (c) bubble rising section. The tube is fixed vertically to the wooden frame, which is pivoted to the iron frame to facilitate free rotation. The liquid is filled in the tube from the top until the interface reaches to our desired height by keeping quick closing valve open and ball valve closed. Subsequently quick closing valve is closed to ensure that all entrapped bubbles are released. Slowly ball valve is opened for few moments to drain the liquid for producing an air void between two valves which is sufficient enough to form Taylor bubble. After formation of air void, both valves are in closing position and after a while only the quick closing valve is opened for a fraction of second by releasing the Taylor bubble which blasts at the interface. The bursting phenomena of Taylor bubble is captured with the help of high speed imaging camera.

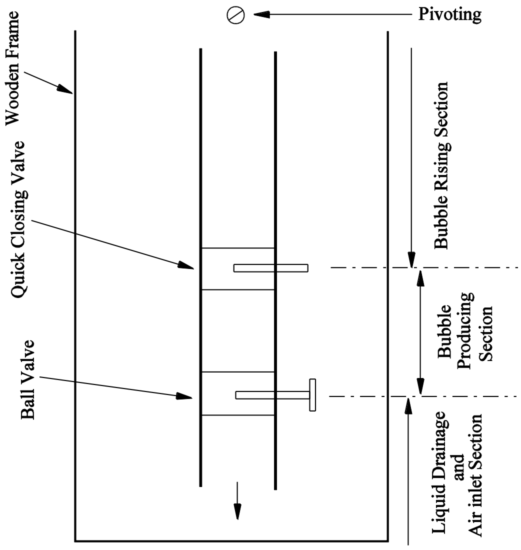


Fig.1 Sketch of tube and arrangement of valves

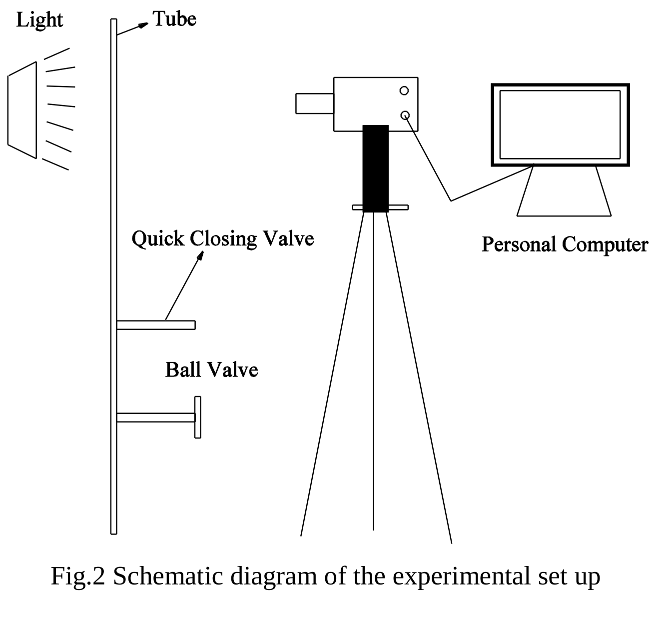


Fig.2 Schematic diagram of the experimental set up

3 Results and discussion

In this work, different liquids are taken as working fluid in the vertical circular tube and bursting phenomena of Taylor bubble is observed carefully. A bubble collapse phenomenon starts from the stage penetration and ends with the wall film drainage by forming the new horizontal interface again. Present work tracks the interface dynamics of the bubble during bursting by extracting some valuable information like top film thinning time, bursting time, wall film drainage time etc. As bubble is moving in a surrounding liquid which acts like an annular liquid jet is falling to the liquid slug, makes the slug with satellite bubbles. Dense of satellite bubble completely depends upon viscosity of the working liquid. In Taylor bubble collapse, satellite bubbles in liquid slug play an important role during the wall film drainage of the liquid. It is observed from the experiment that as liquid viscosity is increasing, bubble top film thinning with blasting takes more time and to form the new horizontal interface after wall film drainage consumes less time due to absence of satellite bubbles in the liquid slug. Liquid like water viscosity is less as compared to silicon oil; it is found that satellite bubbles are more packed in water liquid slug, to the same extent after wall film drainage it will take more time to form the new horizontal interface. The descriptions are reduced by using two dimensionless groups, namely, Bond number (*Bo*) and Archimedes number (*Ar*). Bond number is the ratio of gravitational force to surface tension force and can be expressed as:

$$“Bo = \frac{(\rho_l - \rho_g) g D^2}{\sigma}” \tag{1}$$

Archimedes number is defined as the ratio of gravitational force to viscous force as:

$$“ArBo = \frac{g D^3 \rho_l (\rho_l - \rho_g)}{\mu^2}” \tag{2}$$

Where, ρ_l = Density of liquid phase, ρ_g = Density of gaseous phase, D = Internal diameter of the cylindrical tube, μ = Viscosity of liquid phase, σ = Interfacial surface tension between two phases and g = Acceleration due to gravity.
Collapse of Taylor bubble at interface covers five different stages in its whole life time of bursting. First stage is identified as penetration of bubble towards interface where bullet shape nose of Taylor bubble is just touching to the interface. Immediate phase after accomplishment of penetration is observed as bubble top film thinning. Bubble top film thinning is completely depending on the viscosity of working liquid, whose life time is becoming larger as viscosity of liquid increases. A clear picture of film thinning is observed when silicon oil works as liquid. An extremely thin film blasts which is named as bursting of film on the top of bubble. Film retracts towards the pipe wall quickly just after the top thin film of the bubble ruptures which confirms the cup shape of the Taylor bubble. At the end wall film drains towards the liquid slug as if annular liquid jet is freely falling. During this whole life time of bubble blasting, height of the Taylor bubble is decreasing continuously starting from the top film thinning.

3.1 Taylor bubble bursting stages

Figure 3 retrieves the different stages of life time of Taylor bubble blasting starting from the penetration to the wall drainage. Penetration towards the interface starts at t=0.47 seconds means at this situation bubble just starts touching to the interface. As viscosity of water is very less i.e. 0.001 Pascal sec at room temperature (*Bo* = 49.029 and *Ar* = 6.693733 x 10^7 for 19 mm tube diameter), it is observed that a bunch of satellite bubbles are packed in the liquid slug due to continuous free falling of annular liquid jet. Top film thinning is started just after the penetration stage about at t=0.5 seconds due to continuous liquid drainage. Retraction of the film towards the tube wall is nearly not observed after the top film ruptures due to the less viscosity effect. Wall film thickness is also very less i.e. diameter of the Taylor bubble is approximately equal with diameter of tube. Therefore drainage of wall film takes very less time around 0.15 seconds for the 32 mm length of Taylor bubble as shown in Figure 3. Due presence of huge amount of satellite bubbles in the liquid slug, the recovery of new horizontal interface consumes more time as compared to more viscous liquids.

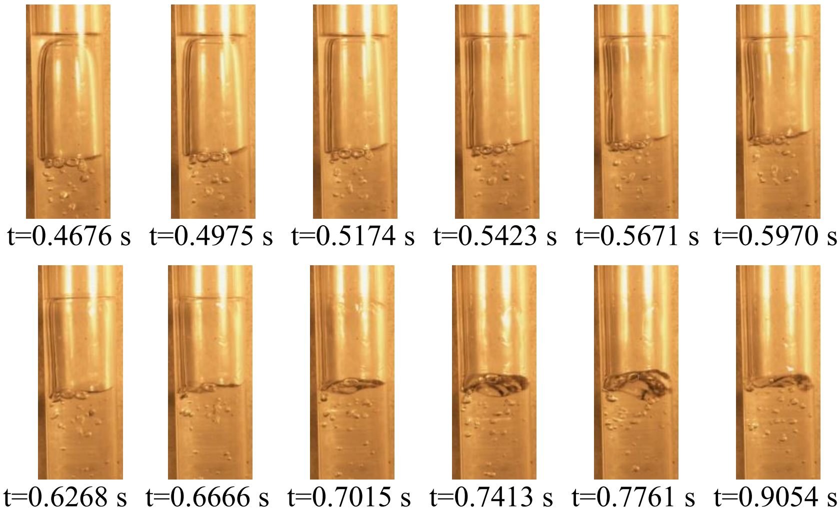


Fig. 1 Different stages of Taylor bubble collapse with time (s) for water as working liquid in 19 mm tube diameter. Bo = 49.029 and Ar = 6.693733 x 10^7

Taylor bubble bursting phenomenon exhibits in more interesting way and many more unique things are observed with little bit enlargement of viscosity of working liquid. Taylor bubble leading edge is described by prolate spheroid, whose curvature is higher for higher viscosities. Figure 4 shows the glycerin as the working liquid with dynamic viscosity 0.950 Pascal sec at room temperature (Bo = 70.705 and Ar = 118.06466 for 19 mm tube diameter). It is observed clearly that during wall film drainage one liquid jet is coming up from the bottom of the semi blasted bubble. The satellite bubbles are not at all observed in the liquid slug zone due to less shearing action of Taylor bubble tail. First stage of bubble blasting i.e. penetration starts around t=0.08 seconds and film thinning and retraction towards the tube wall both are occurring simultaneously as shown in Figure 4. Bullet shape nose of elongated Taylor bubble touches the interface by covering the penetration process followed by leading edge widening and thinning of top film of bubble. Diameter of leading and tail edge of bubble increasing and decreasing respectively as compared with nominal diameter of Taylor bubble at time t=0.1470 seconds. Height of Taylor bubble is reducing continuously as top film thinning is occurred by liquid drainage from t=0.0795 to 0.1585 seconds. Wall drainage starts at t=0.1560 seconds after top film blasts and retracts towards pipe wall, which leads to liquid jet formation at the bottom of bubble and makes the phenomenon more interesting and complex. At t=0.1800 seconds, a clear presence of the liquid jet is observed due to quick draining and falling of wall film to liquid slug zone.

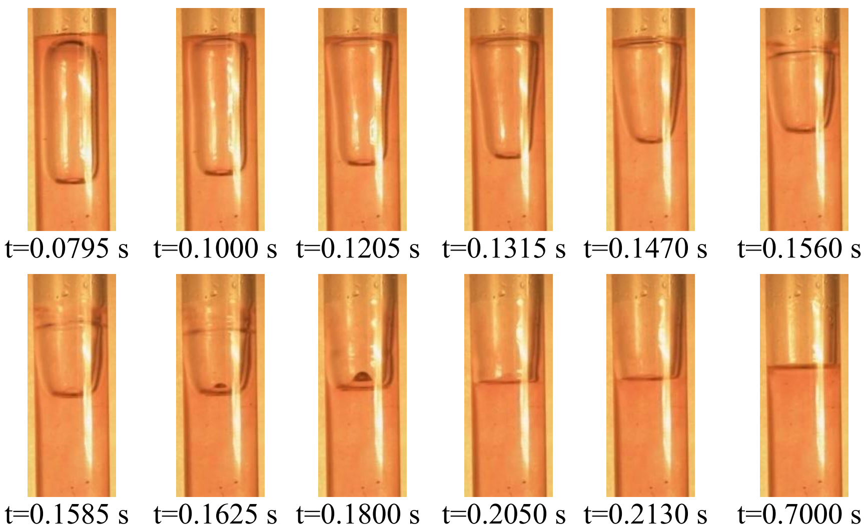


Fig. 2 Different stages of Taylor bubble collapse with time (sec) for glycerin as working liquid in 19 mm tube diameter. Bo = 70.705 and Ar = 118.06466

Figure 5 shows the Taylor bubble bursting in silicon oil liquid with various stages. It is seen in the wake region of the bubble the shed of satellite bubbles are not observed due to viscosity effect (Bo = 154.438 and Ar = 38.80348 for 19 mm tube diameter). In this liquid curvature of Taylor bubble prolate spheroid nose is very high. During the penetration of the bubble into the interface, the nose curvature does not gain flattened shape like water. Nose curvature does not break due to high viscosity of the working liquid as observed from Figure 5 at time t= 0.1609 seconds. During the course of top film thinning and retraction of liquid towards the pipe wall, the shape nose still remains prolate spheroid which is noticed at t=0.1887 seconds. A distinct vision of liquid retraction is marked at t=0.2185 seconds where the leading end of bubble is getting widened with remarkable nose curvature. Due to excess thinning of top film of bubble, the bullet shape nose curvature breaks and gradually is getting flattened as seen at t= 0.2595 seconds and at t=0.3141 seconds shape of top film becomes completely flat with almost retraction is taken place. In addition, bursting of top film is seen around 0.7266 seconds which follows the wall film drainage at t=0.7648 seconds marked with waviness structure of liquid on the wall as found in figure.

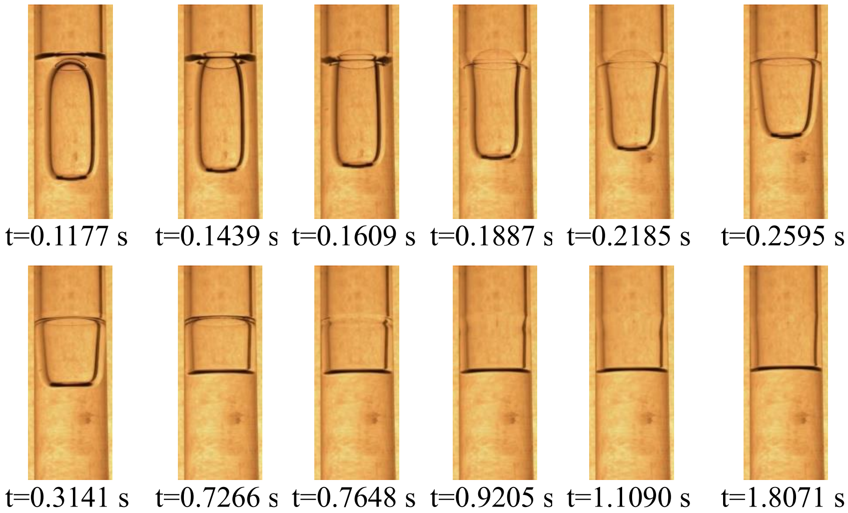


Fig. 3 Different stages of Taylor bubble collapse with time (sec) for silicon oil as working liquid in 19 mm tube diameter. Bo = 154.438 and Ar = 38.80348

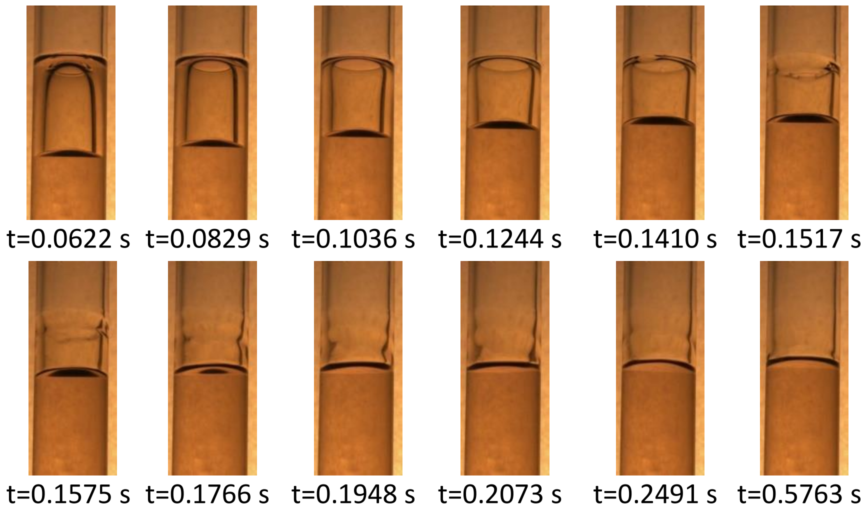
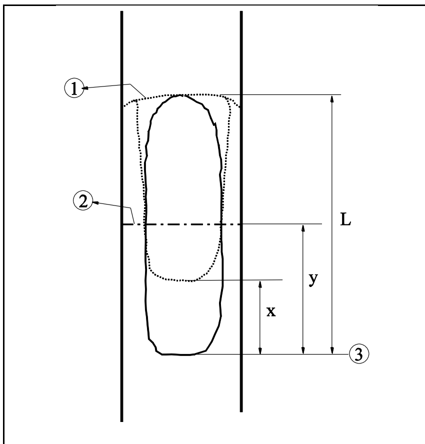


Fig. 4 Different stages of Taylor bubble collapse with time (sec) for mustard oil as working liquid in 19 mm tube diameter.

Figure 6 shows collapse of Taylor bubble where the working liquid is mustard oil with various time steps and phases of blasting life of bubble at interface. In the figure various stages are shown with time instant but one distinguishable feature is observed i.e. the shape of nose is less curved as in silicon oil. When the nose of the bubble penetrates the interface, the bullet shape nose is quickly getting flat which is not seen in case of silicon oil liquid.



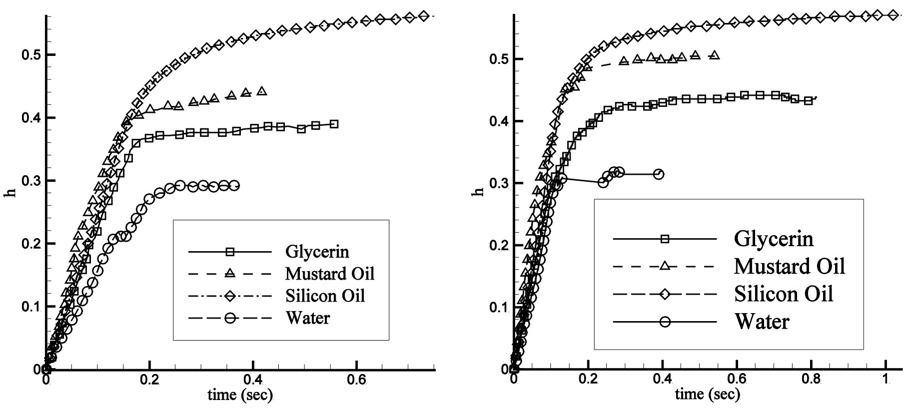
1 = Interface before collapse of bubble.
2 = Interface after collapse of bubble.
3 = Position of tail end of Taylor bubble which is at penetration stage (Reference line).
L = Length of bubble when penetration just starts (Let at t=0).
x = Distance from the reference line to the tail end of bubble at time t from the time of penetration.
y = Distance of the new interface from the reference line = x_{max}
x_{max} = Maximum value of x.

Fig. 7 Sketch of Taylor bubble during collapse

3.2 Variation of h with time during collapse

It is assumed that the length of the Taylor bubble (tracked as solid line bubble) is L, when it starts touching the interface as shown in Figure 7. It has been considered that bubble collapse begins with penetration process with the time t = 0 seconds. At any instant of time t, position of bubble changes as marked with dotted line bubble whose tail end is at a distance of x from the tail end of bubble at t = 0. Formation of a new interface is observed after complete collapse of the bubble, which is at distance of y from the reference line. Distance y can be named as maximum height up to which liquid is deposited after complete collapse of the Taylor bubble from the stage of penetration. A plot is generated between h and time t with different liquids and tube diameters as detected in Figure 8. Expression of h is given by $h = x/L$

The variable h describes the height of liquid deposited relative to Taylor bubble length L in the liquid slug zone during the bubble collapse from the time of penetration in the pipe. An attempt has been made track the complete bursting and drainage time and amount of liquid deposited in liquid slug from the time of penetration. Taylor bubble in water as working liquid takes less time to blast and drain as compared to other liquids. It is observed that for all the liquids, h increases sharply with time and after reaching to a maximum value then h is remaining constant with time. Bending of all curves are nearly 90° except silicon oil liquid curve because the wall drainage in case silicon oil occurs very slowly and for long time.



19 mm ID tube 28 mm ID tube

Fig. 8 Variation of h with time with different liquids for 19 mm and 28 mm ID tube

4 Conclusions

Present effort explains the experimental investigation of Taylor bubble bursting in the cylindrical liquid column with different working fluid in order to understand the physics behind the collapse phenomena.

Following are important observations from the experimental investigation.

- Total bursting time completely depends upon the viscosity of fluid. As from the observation in the silicon oil liquid, Taylor bubble takes more time to burst due to low *Ar*. Liquid is having high *Ar*, takes less time to collapse.
- Top film thinning takes more time in case of liquid is having low *Ar*.
- More satellite bubbles are found in the wake zone in case of water due to low *Bo*.
- Shape of the Taylor bubble looks more slender and rounded off in case of low *Ar* and high *Bo* fluids.

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